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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 5 :		(11) International Publication Number: WO 91/18458
H04L 1/04, H04B 7/12	A1	(43) International Publication Date: 28 November 1991 (28.11.91)

(21) International Application Number: PCT/GB91/00682

(22) International Filing Date: 30 April 1991 (30.04.91)

(30) Priority data:
9010637.8 11 May 1990 (11.05.90) GB

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(81) Designated States: AT (European patent), AU, BE (European patent), CA, CH (European patent), DE (European patent), DK (European patent), ES (European patent), FR (European patent), GB, GB (European patent), GR (European patent), IT (European patent), JP, LU (European patent), NL (European patent), SE (European patent), US.

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: A HIGH FREQUENCY MULTICHANNEL DIVERSITY DIFFERENTIAL PHASE SHIFT (DPSK) COMMUNICATIONS SYSTEM

(57) Abstract

A high frequency transmitter comprises a large number of narrowband channels spaced over a broad bandwidth transmission. In one arrangement input data to be transmitted is demultiplexed (1101) so that sections of data are transmitted in groups of channels at 50 baud (say), each 50 baud channel produces a number of diversity channels modulated using difference phase shift key (DPSK) (103) and then added (105) for transmission. In the receiver, coherent summation (803) of close-bunched channels can be used and semi-coherent channel addition (805) can be used across the complete bandwidth. The received signal is converted to digital form then processed by an FFT circuit to produce frequency bins corresponding to the transmitted diversity channel frequencies. DPSK demodulation is carried out and running averages are carried out in each channel to determine the proportion of times that the phase difference falls within allowed limits (907). A discrimination level (908) determines whether individual channels should be excised (914) because of noise corruption. The remaining channels in groups are then added together to determine each data bit received. In semi-coherent addition (905), the measured phase vectors are added vectorially and the vector sum is used to determine the data bit. In a second arrangement the channels of any one group are arranged in bunches of about 10 spread over a bandwidth of about 2 kHz (the experimentally determined coherence bandwidth) with the bunches spread over the whole transmission bandwidth. The bunch channels are added coherently and the resultants are added semi-coherently as before to determine the group data. The group data is then multiplexed to reproduce the high data rate input data. The arrangement allows high data rates to be transmitted with each of the diversity channels carrying only 50 baud.

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A HIGH FREQUENCY MULTICHANNEL DIVERSITY DIFFERENTIAL PHASE SHIFT (DPSK) COMMUNICATIONS SYSTEM

The invention relates to HF communications and in particular to a multichannel frequency diversity DPSK communications system for the HF radio band.

The purpose of frequency diversity in a communications system is to overcome the vagaries of long range HF radio propagation and interference and thereby improve the ability to reliably detect the transmitted signal with greatly reduced errors and with increased availability.

If transmitted signals are sent using a plurality of different radio frequencies the intended receiver will be able to exploit the diversity reception to:

a. reduce the received bit error rate (BER);
b. avoid co-channel interference from other radio transmissions;
c. overcome multipath time dispersion;
d. overcome channel fading;
e. reduce the effects of time/diurnal variations in propagation;
f. exploit sporadic and transitory propagation;
g. operate with lower transmitter powers;
h. have improved performance (greater data rates);
i. have increased availability (on-demand communications).

Diversity reception requires the provision of two or more (K) transmitted signals, each containing the same message (either simultaneously or time interleaved), on different radio frequency carriers having advantageously uncorrelated propagation characteristics; each carrier frequency defining a diversity channel.

At the receiver the diversity channels must be properly recombined in order to ideally produce an output signal which will have a much lower combined BER (bit error rate) than in any one received channel. In the simplest diversity combiner the channel with the best S/N (signal-to-noise ratio) or lowest BER will be switched to the output. This type of switch 'combining' only works well, however, when at least one channel is always good. When the S/N is simultaneously poor in all the channels the output will be also be poor. A more advantageous method of diversity combining is to sum the received branches after weighting each channel. The channels can be weighted according to their S/N, for example; such systems are known as Maximal Ratio Combining. Using this technique it is possible to coherently combine the wanted signals (if channel co-phasing can be used) whilst at the same time only adding the noise in each channel incoherently. This produces a combined S/N which will be 10 Log(K)dBs better than any individual diversity channel, where the S/N is the same in each. However, to be most effective at HF, the channel frequencies must be separated by more than the correlation bandwidth (the range of frequencies over which noise signals are correlated). This will ensure each channel path will be totally uncorrelated in propagation characteristics such as, fading and multipath as well as interference. Unfortunately, this also means the

phase characteristics for each path will also be very different from baud to baud. This uncorrelated phasing characteristic between channels will make it very difficult to properly co-phase the wanted signals from each path particularly since the S/N will normally be poor in each. At HF therefore, diversity combining can normally only be achieved using noncoherent signal combining.

The object of the present invention is to provide a multichannel diversity DPSK modulated communications system which overcomes the known HF propagation and interference problems and will optimally re-combine DPSK modulated signals of poor S/N and with totally uncorrelated propagation characteristics.

The invention provides a high frequency multichannel communications system having:

a transmitter comprising:

a) input means to receive digital signal data for transmission;
b) the input means connected to a plurality of separate diversity frequency channels distributed so as to produce a signal for transmission over a broad spectral region of the hf band, each channel including a differential phase shift key (DPSK) modulator whereby each channel is modulated at a low data rate; and
c) means to combine the DPSK channel signals for transmission;

and a receiver comprising:

a) receiver means to receive the transmitted signals and convert them to baseband;

b) the receiver means being connected to a plurality of narrowband frequency channels, each channel including a DPSK detector responsive to a respective one of the transmitter diversity frequency signals;

c) means to identify channels corrupted by noise; and

d) semi-coherent processing means to vectorially combine the uncorrupted DPSK detector output signals in each baud period to determine the polarity of the transmitted data bit.

The data rate is preferably selected such that radio path time dispersion does not lead to intersymbol interference. Advantageously the transmission baud rate is between 20 and 100 per sec and is preferably 50 bps.

The modulation level (M) of the transmitted signal, i.e. the number of phase states, may be greater than two. The means to identify noise-corrupted channels is preferably a channel exciser which includes a phase window detector having M phase windows of width $< 360/M$ deg centred on the expected phase directions. Advantageously there is included a counter which takes a running average for each channel, over a pre-determined number of baud periods, of the number of times the detected phase falls within one of the phase windows (HIT). A signal representing the proportion of HITs over the pre-determined number of baud periods for each channel is connected to a discriminator to determine whether the channel is noise corrupted. Noise corrupted channels are then excised. In one arrangement each phase window is

360/2M deg and the discrimination level (HITs to Misses) is set above 1. Preferably the discrimination level applied to the ratio of HITs to MISSes in each channel and the number of baud periods taken to measure the ratio are selected with reference to the resulting signal-to-noise (S/N) ratio and the required reliability of the channel excision.

Preferably each uncorrupted channel signal is added vectorially in the semi-coherent processor and the resultant vector for each baud period is connected to a PSK decoder to determine the data output signal.

In one advantageous arrangement the receiver can be arranged to bunch the uncorrupted frequency channels into groups where the bandwidth of a group is less than the correlation bandwidth, the channels of each bunch being connected to a respective coherent processor and the coherent processor outputs being connected to the semi-coherent processor. Preferably the bunch bandwidth is less than 2kHz.

In a preferred arrangement a combined vector signal phase output from a semi-coherent processor may be connected to the channel excisers to determine channel excision. The detected phase signal in each channel is connected to one input of an error detector with the estimated combined vector signal phase being connected to a second input to the error detector, an output signal from the error detector is connected to a channel exciser whenever the detected error rate exceeds a pre-determined threshold. The detected phase signal is considered to be good if it falls within a pre-determined range from the combined vector phase signal. Advantageously the DPSK signal detected in each receiver

channel is connected to first and second channel excisers and to the error detector; the output from the error detector being connected to both excisers to excise noise-corrupted channels; the first exciser being connected via a semi-coherent channel vector summer and a PSK detector to a data output and the second exciser being connected via a second semi-coherent vector summer to provide the estimated combined vector signal phase input signal to the second input of the error detector.

Erraneous channel 'capture' may be prevented by providing an excision decorrelator at the input to the second exciser used to provide the estimated group phase vector, the decorrelator being effective to prevent the number of excised channels from exceeding a pre-determined value.

In one arrangement the transmitter may include a demultiplexer whereby a high rate of input data to the demultiplexer is divided into groups of different frequency channels, each channel transmitting at a low data rate between 20 - 100 bps. In this arrangement the receiver includes a multiplexer to reproduce the higher data rate transmitted signal. Preferably the channels of any one multiplexed group are interleaved with the channel of every other group. By combining high modulation levels with the parallel demultiplexed data, even higher transmission rates can be achieved. In narrowband channels may be provided, spread over a 1 MHz bandwidth.

Preferably the data is differential phase shift key (DPSK) modulated in each channel. The receiver preferably includes an analogue to digital

converter connected to a Fast Fourier Transform (FFT) processor which has a number of frequency bins equal to the number of transmitted frequency channels. The signal phase is then detected in each frequency bin.

In the above arrangements the signal-to-noise of the received data signal may be improved by modulo-2 spreading the transmitted signal with a pseudorandom code (by a pseudo random number generator: PNG) and then despreading the signal in the receiver by means of a replica code. Advantageously the receiver is synchronised to the received signal by means of suitable timing signals. In the preferred arrangement data at 1 bps is spread using a PNG code of 50 bps and in the receiver the de-spread signal is summed over 1 sec or 50 received bits to determine the transmitted data bit polarities.

The invention will now be described with reference to the accompanying Drawings of which:

Figure 1a is a schematic block diagram of a frequency diversity transmitter employing differential phase shift key (DPSK) modulation;

Figure 1b illustrates wideband frequency diversity;

Figure 1c illustrates narrowband frequency diversity;

Figures 1d to 1f illustrate respectively BPSK (1 bit per symbol or modulation level M=2), QPSK (2 bits per symbol, M=4) and 8PSK (3 bits per symbol, M=8);

Figure 2 shows graphs of bit error rates (BER) against signal-to-noise ratios (SNR) for different modulation (M) levels;

Figure 3 is a graph showing HF radio interference characteristics;

Figure 4 is a graph showing the signal level probability function as a function of receiver bandwidth;

Figure 5 shows an arrangement for converting a narrowband transmitted spectrum into parallel diversity channels;

Figure 6a is a block diagram illustrating the vector addition of detected signal phases in parallel diversity channels in a semi-coherent processor;

Figure 6b graphically illustrates the vector addition;

Figure 6c illustrates the data bit decision process;

Figure 6d is the theoretical probability density function (PDF) for random noise phase shifts at the receiver input;

Figure 6e illustrates the PDFs for BPSK signals for two different signal-to-noise ratios;

Figure 6f shows the superimposition of phase windows on the BPSK PDF to determine a measure of channel interference;

Figure 6g illustrates implementation of the Figure 6f scheme for channel excision prior to semi-coherent phase vector summation;

Figure 7 shows graphs of BER against SNR using semi-coherent channel combining for a number of different diversity channels;

Figure 8 is a block diagram of a receiver circuit including coherent processing of channels within bunches in addition to semi-coherent processing of the channel bunches;

Figure 9 is an alternative to the Figure 6g arrangement in which received phase vectors are compared to estimated phase vectors and the error rate in this comparison is used to determine channel excision;

Figure 10 is a phase diagram illustrating operation of the error

detector in the Figure 9 arrangement;

Figure 11 is a block diagram of a demultiplexed transmitter enabling high rates of data transmission by means of 50 bps channels; and

Figure 12 is a modification of the communications system employing spread spectrum data transmission and coherent receiver signal processing.

Figure 1 shows how phase modulated transmitted carrier signals for the diversity system according to the present invention may be created. Input data 101 is used to modulate K different carrier diversity frequencies 102 using Differential Phase Shift Keying (DPSK) modulators 103. The outputs 104 from the K diversity modulators are summed in an adder 105 to produce the signal 106 for transmission via a radio transmitter and aerial. The K channel frequencies may be spaced over just a few kiloHertz (107) or over several megahertz (108) of transmission spectrum, however the bandwidth of each channel is much narrower than the overall bandwidth.

Widely spaced diversity channels will provide protection against long term time/diurnal variations in propagation because the receiving algorithm is capable of selecting those frequencies which can propagate from those which cannot (as the MUF and LUF changes). This level of frequency diversity will therefore also provide a means for automatic frequency management of radio circuits as well as avoiding the normal interference and fading problems.

Narrowband (eg. 3kHz) diversity will not have the same long term propagation advantages as wideband but it can still provide substantial

protection against interference and multipath particularly if the transmitted signal has 10 or more diversity channels. The number of channels which can be deployed will depend on the symbol rate used to transmit the data and the total bandwidth allocated.

The symbol rate of the diversity channels, and therefore the message (101) data rate, will also be limited by the prevailing HF propagation constants to a small definable range of possible values. The highest usable rate is controlled by the maximum radio path time dispersion, since it is necessary to have a minimum baud length which is always greater than this to overcome intersymbol interference. Typically this will be 10 milliseconds for most circuits so the highest rate must be less than 100 bauds/sec. The lowest symbol rate is controlled by the maximum doppler frequency shift observed over the radio paths and also the transmitted symbol phase modulation (M) level (ie. DBPSK or DQPSK and D8PSK etc.). For a doppler of 1Hz and DBPSK modulation the minimum symbol rate must be greater than 20 bauds/sec. (For the embodiment of the invention now described, a symbol rate of 50 bauds/sec. has been chosen). For higher dopplers and phase modulation levels the symbol rate must be correspondingly increased but only to a maximum of 100 bauds. Higher modulation levels (M) are less tolerant to doppler and phase shifts because the data is coded onto the transmitted carrier at much closer phase states. For BPSK (109) the signal requires only two phase states (ie, 0 and pi) to transmit the data, whereas QPSK (110) needs 4 states (ie, 0, pi/2, pi, and, 3pi/2), and 8PSK requires 8 phases (ie, 0, pi/4, pi/2, 3pi/4, pi, 5pi/4, 3pi/2, and 7pi/4). For higher modulation levels therefore the received signal will be much more

sensitive to frequency, phase or noise perturbations because a correspondingly smaller change in phase will be able to transmute the data from its correct value to an adjacent incorrect value. It is for these reasons the data values are arranged (prior art) to change by only one bit position between adjacent phase states, ie. binary "100" (112) and "101" (113) and "000" (114).

The effect of noise on the different phase modulation levels (M) is illustrated by Figure 2. At 10 dBs S/N the BER for DBPSK (M=2) is 1*10(-5) (201). For DQPSK (M=4) it is 6*10(-3) (202). For D8PSK (M=8) it is 9*10(2) (203) and for D16PSK (M=16) it will be 1.5*10(-1) (204).

Higher modulation levels would normally therefore be avoided for HF communications since they require significant increases in signal power to effect the same BER as, for example, DBPSK. For example for a BER of 10(3) to be achieved using DBPSK a S/N of 7.5 dBs (205) is needed whereas it requires 23 dBs for D16PSK (206).

The symbol rate of the transmitted signal is also very important because it defines the detection bandwidth required in each diversity channel of the receiver. Lower data rates need less bandwidth and are therefore less likely to be corrupted by interference. Figure 3 shows the typical interference spectrum for the HF radio band. Wideband detection (301) introduces much higher levels of received noise floor than that for narrowband (302). This effect occurs because nearly all the signals transmitted in the HF band are narrowband. This produces gaps in the received spectrum if the receiver bandwidth is also very small (say 100

Hz). Figure 4 illustrates this more clearly as a Cumulative Probability Density Function (CPDF) plot for HF interference in received bandwidths of 100 Hz to 100 kHz. It can be shown, for example, that the probability of falling on any random 100 Hz channel, with less than 10 dBm volts, is 70% (401) whereas the probability for a 3 kHz channel will be only 23% (402). A symbol rate of 50 bauds/sec will therefore provide good interference selectivity because the detection bandwidth can be less than 100 Hz.

Figure 5 is one arrangement for converting a narrowband (107, Figure 1) transmitted RF spectrum into K parallel diversity channels. A receiver antenna 501 is connected to a radio receiver 502 which converts the frequency of the transmitted signal down to an audio baseband spectrum (503). For this example the signal is assumed to be sent as a single sideband (USB) format in a 3 kHz bandwidth but the principles remain the same if a wideband RF transmission (108, Figure 1) is used. The receiver output 504 is synchronously detected in respective product detectors 505 using reference sub-carrier signals 506. The detector outputs are then filtered to the necessary bandwidth (<50 Hz) by lowpass filters 507 to exclude any out-of-band interference or noise (not shown). The K diversity channel signals are then processed by a DPSK Diversity Demodulator and Combiner 508 to produce the enhanced data output 509.

Figure 6a shows the proposed semi-coherent channel signal addition process to be used in the diversity combiner 508. Differential Phase Detection 601 is done over each baud period (20ms) in each of the 10

frequency channels. The frequency diversity channels, which should all have identical phase, are then vectorially added 603 and a decision algorithm PSK decoder 604 is employed to determine the transmitted data bit polarities. Figure 6b illustrates the vector (unity normalised) addition of three such differential phase detector outputs 605, 606, 607 with vector 608 representing the vector sum. Ideally for perfect S/N all these vectors should be in line with "0" (609) but noise and interference varies the detected phase differently in each diversity channel. In a DBPSK modulation system, where the phase difference should be either 0 or pi, as indicated in figure 6c, the decision algorithm 604 can be arranged such that the data bit is resolved as "0" (610) if the vector sum 608 falls within the range of angles 0 +/- pi/2 and will be a "1" (611) if it falls within pi +/- pi/2. Where higher order PSK modulation is used , DQPSK for example, the decision window (0 +/- pi/2 above) is made appropriately smaller about the expected phase change within a baud period.

Where 2-phase DPSK is employed we expect the DPSK detector output to be 0 or pi degs (109, Figure 1) at the baud rate of 50/sec. Thus the DPSK output is sampled 50 times a second. If interference is present this does not have exactly the same frequency or expected phase as any one good signal channel and will cause the measured signal to phase rotate in that channel. If there were just random noise phase shifts at the DPSK input this would lead to a uniform phase Probability Density Function (PDF) 612 (Figure 6d) at the DPSK detector output (602). For the 2-phase DPSK system we can define the detection windows for a data "0" as 0 deg +/- 90 degs and "1" as 180 deg +/- 90 deg because the phase PDF distribution is centred on 0 deg and 180 deg although the detected

phase can be deviated away from the true position by random noise as shown in Figure 6e. For S/N = infinity the received phase will be either 0 deg or 180 deg (613, 614). For lower S/N ratios the phase will increasingly (for falling S/N) have a probability of being further way from 0 and 180 degs. A good S/N PDF is shown by 615, 616 and a poor S/N PDF by 617, 618. For detection therefore a signal phase which lies within +/- 90 degs of the phase positions 0 and 180 degs will be detected as 0 and 180 degs respectively (i.e. "0" or "1"). Figure 6e suggests a method for directly measuring signal quantity and its potential for use in an interference excision algorithm without any prior knowledge of the data being transmitted. Figure 6f shows the PDF of phase for a DBPSK signal of modest S/N ratio. It can be seen that the phase has a higher probability of being within a small range of (either) 0 deg or 180 degs. If the received signal was just random noise/interference this would not be true, as indicated by Figure 6d. For noise or interference discrimination, therefore, we reduce the phase windows (621, 622), about the expected phase directions by say half, to +/45 degs. A running average is then taken for each channel, over a number of baud periods, of how many times the detected phase falls within the expected windows 621, 622 (Hit) and the number of times it falls outside (Miss) the expected windows, as indicated in Figure 6f. If the ratio of Hits to Misses is much greater than 1 then the channel may be considered good. For lower S/N this Phase PDF ratio will be much lower but >1. For random noise, for example, it will be an average 1 because there is an equal probability of being a Hit or a Miss (from 612).

Figure 6g shows how the Phase DPSK decoder 623 is connected via an input noise filter 624 to a detected receiver channel input 625 to operate in conjunction with a PDF detector 626 and as an interference/noise channel exciser system. A Hit/miss count in the exciser 626, as described with reference to Figure 6f, would be made at the detector output 627 and if this exceeds a specified (S/N) threshold 630 the detected signal in the receiver channel 627 will be connected to a subsequent phase vector summing circuit 628, as described above, by the switch 629. The setting of the S/N threshold in the exciser 626 is critical to the proper optimum operation of the system because this decides what the quality of the channel signal shall be before it is added to the phase vector summing circuit 628. If, for example, the number of channels being added is very large, say 100, then it is necessary to include all those channels having a S/N of > -4.5 dBs (a BER of 3.5*10(-1), Figure 2, 207) because when added together they can produce a resulting equivalent signal of > +7 dBs (ie. a BER of 1*10(3), see Figure 7, 707). When the number of channels is much smaller, say 10, then only channels of > +2 dBs (BER of 1*10(-1), 701) can be used to produce a resulting equivalent signal of > +7 dBs (BER of 1*10(-3), 703) because the combined output from the 10 diversity channels will be 1*10(-3) BER, 702 at 2 dBs S/N.

The time taken (the number of baud periods) to measure the Hit to Miss ratio will depend on the acceptable S/N ratios for the signals and the required reliability of excision process. In general the poorer the signal-to-noise ratio, then the longer it will take to measure the phase PDF ratio. For small numbers of diversity channel vector combining the S/N ratio has to be good (ie.>2 dBs for 10 channels) so the number of

bauds needed for calculating the Phase PDF can be quite small. Typically this may be done over a 20 baud period (0.4 sec.). If we count 20 Hits (very low noise probability) then the switch 629 in the excision circuit (Figure 6g) is closed while if the number is 10 (random noise) then the switch 629 is opened. A threshold for channel acceptance is therefore set between 10 and 20 Hits in this example. Using the binomial theory, the probability of 20 Hits being due just to noise is 1 in 106 so the probability of a false channel excision control is very small. The probability of exceeding a specified threshold number of Hits due to noise can be reduced by counting over a larger number of baud samples.

The inventor has shown that even though there may be a poor demodulation signal in the individual channels (with a poor estimate of phase change), when the vector sum is done followed by PSK detection there is a significant processing gain.

The effect of channel addition can be seen more clearly with reference to Figure 7. This shows graphs 704 to 706 of the required channel signal-to-noise (dBs) against bit error rate (BER) for the addition of 1, 10, and 100 channels respectively for DBPSK (M-ary = 2). Surprisingly this shows a significant improvement in using more than one channel despite the fact that DBPSK demodulation is used prior to channel addition (See Figure 6a).

Experiment has shown that there are normally correlation bandwidths of greater than a few kiloHertz in the HF spectrum. This is the extent of the frequency band over which the transmission dispersion

characteristics are correlated and the phases of the received signals are sensibly the same. To take advantage of this property the transmission of some of the diversity channels may be arranged such that some of the channels are bunched in frequency bands of about 1 or 2 kHz across the occupied frequency spectrum. True correlation techniques can then be applied to each of the channels in a bunch. Thus for example, each bunch might comprise 10 channels. True coherent processing would be used for each bunch of 10 channels (a maximum of 10 dBs of processing gain) and then semi-coherent processing will be applied to the bunches (as done in Figure 6a) to re-combine all the remaining (bunched) frequency diversity channels. This approach will give greater processing gain and allow even lower SNR reception and therefore will lead to improved communications performance and reliability in the presence of background noise.

Figure 8 shows this process more clearly and shows how interference excision would be implemented. The input channels 801 in the bunch correlation bandwidth are first separately excised (802) before being coherently summed (ie. before DPSK detection) in 803, to form the 'bunch channel' sum signal. If more channel bunches are used to form the complete diversity group (which may be widely spaced in frequency), then these are semi-coherently added together in 805 after the signals from 803 are differentially phase demodulated in 804. The vector sum 810 output from 805 is decoded in the PSK phase detector 806 to produce the data output 807 for the group to form the user data signal. Since the signals in the 'bunch' diversity channels should have the same phase characteristics (being contained within a correlated bandwidth) the

signal at the output of the coherent summer 803 must have the same signal phase as in any of the diversity channels, but with a greatly enhanced S/N. In gaussian noise this improvement is 10 log(N) where N is the number of channels in the 'bunch'. The combined sum vector signal phase 808 from the summer 803 is therefore a more accurate measure of the actual phase of every channel signal. This can therefore be used to increase the accuracy of the excision modules (802) phase PDF Hit/Miss ratio counter (809) because we now know what the phase of each channel signal should actually be. This increased accuracy will significantly reduce the probability of a false phase PDF count and also reduce the time taken to make a channel excision decision. The performance of a 100 channel group system (say) based on Figure 8 would yield a much greater processing gain than the previously described semicoherent system (Figures 5 and 6). Figure 7 shows, for example, that the semi-coherent system would give a gain of about 12 dBs for 1*10(-3) BER (707 from 703 =12 dBs). For a system like Figure 8 where there could be 10 channels/bunch and 10 bunches/group the gain would be about 16 dBs (10 + 6 dBs) ie. 10Log(10) + 702 from 703.

The alternative arrangement, discussed above, for the channel excision circuit previously suggested in Figure 6g has been found to improve the phase PDF detector and the channel excision process in general. Figure 9 shows the improved arrangement for one of many channels (K). The received channel input 901 is differentially detected by a phase detector 902 to find the change in relative phase of the signal since the last baud. The data output 916 from the circuit is determined using a Data Group Detector 903 composed of a data channel exciser 904, a

vector summer 905 and an MPSK decoder 906. In this arrangement the MPSK decoder 906 converts the phase of the vector summer 905 output to a binary code (gray) as is known in the art. Each channel input to the vector summer 905 is excised if the channel quality falls below a predefined threshold. In this particular channel the exciser 904 will be activated if the count of a BPSK error detector 907 exceeds a set threshold 908 in a given period of time (or baud count). The BPSK error detector 907 thus replaces the phase PDF detector 626, Figure 6g, in the previous arrangements. The purpose of the BPSK error detector 907 is to compare the phase of the channel signal 909 with that produced by an Estimated Group Vector Detector 910 composed of a channel exciser 911 and a vector summer 912. The vector summer 912 produces the estimated signal vector 913 from the combined inputs of the unexcised channels in the diversity group (as is also done in the data group detector 903). The estimated signal vector 913 therefore represents the sum of all the good channels in the diversity group and will therefore have a better signal to noise ratio (S/N) than any one individual channel in the group. In the BPSK error detector 907 the phase of the channel signal 909 is compared to the phase of the estimated group vector 913 as shown in Figure 10. The BPSK error detector 907 will count an error whenever the phase of the channel signal 1001 exceeds the estimated signal vector 1002 phase by more than +/- pi/2. The signal 1003 is considered correct if it lies within +/- pi/2 of the estimated signal vector 1002.

This alternative system is better than the previous Hit/Miss phase PDF arrangement because a direct comparison is now made between each measured channel phase and what it should actually have been. In the

previous arrangement a test was made (Figure 6f) to see if the signal phase "fitted" the expected phase (PDF) for the given modulation level.

In the Figure 9 arrangement the BPSK error count is always made as shown in Figure 10, irrespective of the modulation level used to transmit the data (eg. D8PSK), whereas in the previous arrangement the phase PDF Hit and Miss windows have to be changed to suit the modulation level being used.

A refinement to the channel excision process is also necessary (in the estimated group vector detector 910) to prevent erroneous channel 'capture'. This is done by using a channel decorrelator 914. The decorrelator 914 is used to prevent a small number of channels "capturing" the excision process and locking out all the other channels. The decorrelator 914 operates to stop the number of unexcised channels falling below a defined ratio 915, for example 50%. The decorrelator 914 unexcises some of the poor channels to the summer 912 to prevent capture. Adding these poor channels back to the summing process produces a negligible effect on the data output bit error rate.

Throughout the specification the bandwidth of the individual channels is described as narrowband since it is much smaller than the occupied bandwidth of the overall system. In addition, the rate of data transmission, typically 50 bps per channel, is selected to be low enough such that a signal period is longer than a typical multipath impulse response (about 10 ms). The plurality of channels enable the system to achieve a significant signal processing gain in order to operate the

system specifically in much higher ambient background interference and noise levels than the individual channel signals themselves.

The diversity channels can also be divided into groups and a demultiplexer provided in the transmitter, connecting the input means to each group whereby a higher data rate input signal can be demultiplexed to produce a multiplicity of parallel lower data rate channels in each diversity group, and in the receiver the means to recombine the channels includes a multiplexer to reproduce the higher data rate transmitted signal. Figure 11 shows one such example. Data at 200 bps for transmission is connected to the input 1100 (C_o) of a demultiplexer 1101, providing four data output channels 1102 (C_1 - c_4) each carrying 50 bps. Each output channel 1102 is connected to 10 frequency modulators to provide 10 diversity channels (f_{11} ... f_{110}; ... (f_{41} ... f_{410}; the frequencies corresponding to each of the channels C_m being interleaved with frequencies from each of the other channels. Thus the order of frequencies may be, for example, f_{11}, f_{21}, f_{31}, f_{41}, f_{21}, f_{22}, f_{32}, f_{42} ... etc. In the receiver the signals detected in the four paralleled 50 bps channels are connected to a multiplexer to reconstitute the 200 bps data output. By this means transmission data rates of 200 bps, and higher, can be achieved while preserving multipath discrimination, interference rejection and anti-fading characteristics. Higher data rates may be also be more easily realised if higher phase modulation levels (M) are also used in combination with channel multiplexity.

The channels of any one multiplexed group are preferably interleaved

with the channel of every other group such that the channels of each particular group are spread throughout a broader transmission bandwidth. The number of sub-channels used is optional, but in the limit this depends on the total number of diversity channels available and the required data rate. In general, the more sub-channels used the greater will be the data rate and/or the higher will be the signal processing gain. Thus generally the highest possible bandwidth should be used to achieve the highest processing gain. This in turn will allow the system to be operated at the lowest signal to noise or interference ratio.

In one possible arrangement having relatively few diversity channels the communications system has say 10 narrowband channels spread over a 1 MHz bandwidth. In this arrangement interference corrupted, or poorly propagating, channels are excised in the receiver before the channels are recombined. By this means the despreading/diversity combining and detection mechanisms in the receiver are optimised and processing gains are produced to enable weak transmitted signals to be recovered from an otherwise poor radio circuit condition.

Thus by using a number of diversity channel frequencies to transmit each data bit it is possible to recover the transmitted message from a very noisy received signal spectrum. Those channels with unacceptably high noise or interference can be removed without producing serious degradation because each data bit is transmitted using so many channels and it only requires one or more good S/N channels to receive a data bit correctly.

In the above arrangements the data is differential phase shift key (DPSK) modulated in each diversity channel. In addition, where differential phase shift key (DPSK) modulation is employed, this has been shown to be operable from M-ary number 2 to at least 16 (where M is the modulation level used). In the semi-coherent phase processing described in the above arrangements the difference phases relevant to an element of data, in all channels in a group, are added vectorially and the resultant vector is used to determine the data element. Thus the combined signal is assumed to be the same as the wanted signal. On the face of it this would appear to be an incorrect assumption since it is derived from all channels and the preponderance of these may be noisy. However, computer simulations and experiments have shown that this arrangement works very well and the combined output from all the channels is a good representation of the wanted signal.

The phase of this signal can therefore be used to measure more accurately the phase PDF (Figures 6d - f) in each channel. This is done by counting the number of times the channel signal phase falls within defined limits of the combined signal phase (Hits). Channels which fail to achieve a desired Hit count are then excised from the combined signal and this in turn improves the accuracy of the combined signal phase. This results in a rapidly converging excision system. By including in each channel an error detector and an exciser where the resultant phase vectors for each signal are connected to the error detector where they are compared to the corresponding measured phases in the diversity channels, an output signal is produced therein corresponding to the proportion of channel phases which lie within pre-determined phase

limits of the resultant phase vectors. This output signal is then connected to the exciser where the channel is accepted or excised for data decoding in dependence on whether the measured proportion exceeds a further predetermined limit.

The error detector output may also be used to control a channel exciser at the input to the phase vector adder whereby only good channel signals determine the resultant phase vectors. In this arrangement the output from the error detector is connected to a decorrelator which compares the proportion of channels for excision to a predetermined limit and prevents channel excision numbers exceeding the limit.

The receiver may include an analogue to digital converter connected to a fast Fourier transform (FFT) processor which has a number of frequency bins equal to the number of transmitted frequency channels. The interference excision means then includes means to measure the signal phase in each frequency bin and to determine the quality of each received frequency diversity channel, and to excise channels where interference is subsequently detected. Each channel is measured for quality by comparing its phase with the expected values and a count is made of the number of times it looks like the expected phase (a Hit). If this count exceeds a fixed threshold level then the channel is used. If the channel count is less than the threshold then the channel output is excised before it can be added in a vector summer.

A further refinement for overcoming noise is shown in Figure 12. A means is shown whereby the Vector Sum (905 or 805 or 617 or 603) output, of the data signal, may be enhanced in S/N by integrating (summing) the

signal over several bauds (10 or 100 data bits, for example). In this means a lower user data rate, of say 1 bps, may be transmitted using a 50 bps DBPSK signal by Modulo 2 multiplying (spreading) the lower user data rate with a pseudo-random code (of 50 bps).

At the receiver the data modulated 50 bps code is re-multiplied (de-spread) by a replica code of the same sequence, reproduced in the receiver, (being previously synchronised using Time Of Day and Word Of Day). The de-spread signal is then summed over 1 second or 50 bits (50 bps/1 bps = 1 sec.) to determine the transmitted data bit polarities.

In Figure 12 the summed (prior to PSK decoding) diversity channels 1200, of 50 bps, is multiplied (1201) by the Pseudo Random Code 1202, of 50 bps, produced by the code generator 1203. Generator 1203 is designed to reproduce the same coded sequence used to spread the data in the transmitter. An integrator 1204 sums the code products from 1201 over the user data rate period and a polarity bit detector 1205 determines the bit polarity at the end of the integration time (1 sec.). The signal processing gain achieved by the mechanism shown in Figure 12 will be 10Log(n), where n is the number of coded bits used to transmit each data bit. By this means the user data when transmitted over the diversity channels will be much less sensitive to interference and noise and the BER achieved will be greatly reduced. For example, in Figure 7 the BER for 10 DBPSK diversity channels at -5 dBs S/N will be about 20%, 708. If a 10 bit (n=10) signal integration 1204 is used (5bps user data rate) the processing gain will be 10 dBs and the error rate will fall to less than 1*10(-4).

Claims

1. A high frequency multichannel communications system having: a transmitter comprising:

a) input means (101) to receive digital signal data for transmission;

b) the input means connected to a plurality of separate diversity frequency channels (104) distributed so as to produce a signal for transmission over a broad spectral region of the hf band, each channel including a differential phase shift key (DPSK) modulator (103) whereby each channel is modulated at a low data rate; and

c) means (105) to combine the DPSK channel signals for transmission;

characterised in that the receiver comprises:

a) receiver means (502) to receive the transmitted signals and convert them to baseband;

b) the receiver means being connected to a plurality of narrowband frequency channels, each channel including a DPSK detector (505) responsive to a respective one of the transmitter diversity frequency signals;

c) means (626) to identify channels corrupted by noise; and

d) semi-coherent processing means (628) to vectorially combine the uncorrupted PSK detector output signals in each baud period to determine the polarity of the transmitted data bit.

2. A high frequency multichannel communications system as claimed in claim 1 characterised in that the data rate is selected such that radio path time dispersion does not lead to intersymbol interference.

3. A high frequency multichannel communications system as claimed in claim 2 characterised in that the transmission baud rate is between 20 and 100 per sec.

4. A high frequency multichannel communications system as claimed in claim 3 characterised in that the transmission baud rate is 50 bps.

5. A high frequency multichannel communications system as claimed in any one preceding claim characterised in that the modulation level (M) of the transmitted signal, ie the number of phase states, is greater than two.

6. A high frequency multichannel communications system as claimed in any one of claims 1 to 5 characterised in that there is included a channel exciser (629) to excise channels identified as noise corrupted.

7. A high frequency multichannel communications system as claimed in any one preceding claim characterised in that the means to identify noise-corrupted channels includes a phase window detector (626) having M phase windows of width $< 360/M$ deg centred on the expected phase directions.

8. A high frequency multichannel communications system as claimed in claim 7 characterised in that there is included a counter which takes a running average for each channel, over a pre-determined number of baud periods, of the number of times the detected phase falls within one of the phase windows (HIT) and a signal representing the proportion of HITs over the predetermined number of baud periods for each channel is connected to a discriminator to determine whether the channel is noise corrupted.

9. A high frequency multichannel communications system as claimed in claim 8 characterised in that each phase window is $360/2M$ deg and the

discrimination level (HITs to Misses) is set above 1.

10. A high frequency multichannel communications system as claimed in claim 8 or 9 characterised in that the discrimination level applied to the ratio of HITs to MISSes in each channel and the number of baud periods taken to measure the ratio are selected with reference to the resulting signal-to-noise (S/N) ratio and the required reliability of the channel excision.

11. A high frequency multichannel communications system as claimed in any one preceding claim characterised in that each uncorrupted channel signal is added vectorially in the semi-coherent processor and the resultant vector for each baud period is connected to a PSK decoder to determine the data output signal.

12. A high frequency multichannel communications system as claimed in any one preceding claim characterised in that the receiver is arranged to bunch the uncorrupted frequency channels into groups where the bandwidth of a group is less than the correlation bandwidth, the channels of each bunch being connected to a respective coherent processor (803) and the coherent processor outputs being connected to the semi-coherent processor (805).

13. A high frequency multichannel communications system as claimed in claim 12 characterised in that the bunch bandwidth is less than 2kHz.

14. A high frequency multichannel communications system as claimed in any one preceding claim characterised in that a combined vector signal phase output (808) from a semi-coherent processor (803) is connected to the channel excisers (802) to determine channel excision.

15. A high frequency multichannel communications system as claimed in any one of claims 1 to 6 or 11 to 14 characterised in that the detected

phase signal in each channel is connected to one input of an error detector (907) with the estimated combined vector signal phase being connected to a second input (913) to the error detector, an output signal from the error detector is connected to a channel exciser (914) whenever the detected error rate exceeds a pre-determined threshold (908).

16. A high frequency multichannel communications system as claimed in claim 15 characterised in that the detected phase signal (909) is considered to be good if it falls within a pre-determined range from the combined vector phase signal (913).

17. A high frequency multichannel communications system as claimed in claim 16 characterised in that the DPSK signal detected in each receiver channel is connected to first and second channel excisers (904, 911) and to the error detector (907); the output from the error detector (907) being connected to both excisers to excise noise-corrupted channels; the first exciser (904) being connected via a semi-coherent channel vector summer (905) and a PSK detector (906) to a data output (916) and the second exciser (911) being connected via a second semi-coherent vector summer (912) to provide the estimated combined vector signal phase input signal (913) to the second input of the error detector.

18. A high frequency multichannel communications system as claimed in claim 17 characterised in that erraneous channel 'capture' is prevented by providing an excision decorrelator (914) at the input to the second exciser (911) used to provide the estimated group phase vector (910), the decorrelator (914) being effective to prevent the number of excised channels from exceeding a pre-determined value (915).

19. A high frequency multichannel communications system as claimed in

any one preceding claim characterised in that the transmitter includes a demultiplexer (1101) whereby a high rate of input data (1100) to the demultiplexer is divided into groups (1102) of different frequency channels, each channel transmitting at a low data rate between 20 - 100 bps and the receiver includes a multiplexer to reproduce the higher data rate transmitted signal.

20. A high frequency multichannel communications system as claimed in claim 19 characterised in that the channels of any one multiplexed group are interleaved with the channel of every other group.

21. A high frequency multichannel communications system as claimed in any one preceding claim characterised in that the receiver includes an analogue to digital converter connected to a Fast Fourier Transform (FFT) processor which has a number of frequency bins equal to the number of transmitted frequency channels and the signal phase is detected in each frequency bin.

22. A high frequency multichannel communications system as claimed in any one preceding claim characterised in that the signal-to-noise of the received data signal is improved by modulo-2 spreading the transmitted signal with a pseudorandom code produced by a pseudo random number generator (PNG) and then despreading the signal in the receiver by means of a replica code.

23. A high frequency multichannel communications system as claimed in claim 22 characterised in that data at 1 bps is spread using a PNG code of 50 bps and in the receiver the de-spread signal is summed (1204) over 1 sec or 50 received bits to determine the transmitted data bit polarities.

24. A high frequency multichannel communications system as claimed in

any one preceding claim characterised in that the receiver is synchronised to the received signal by means of suitable timing signals.

Fig.1a.

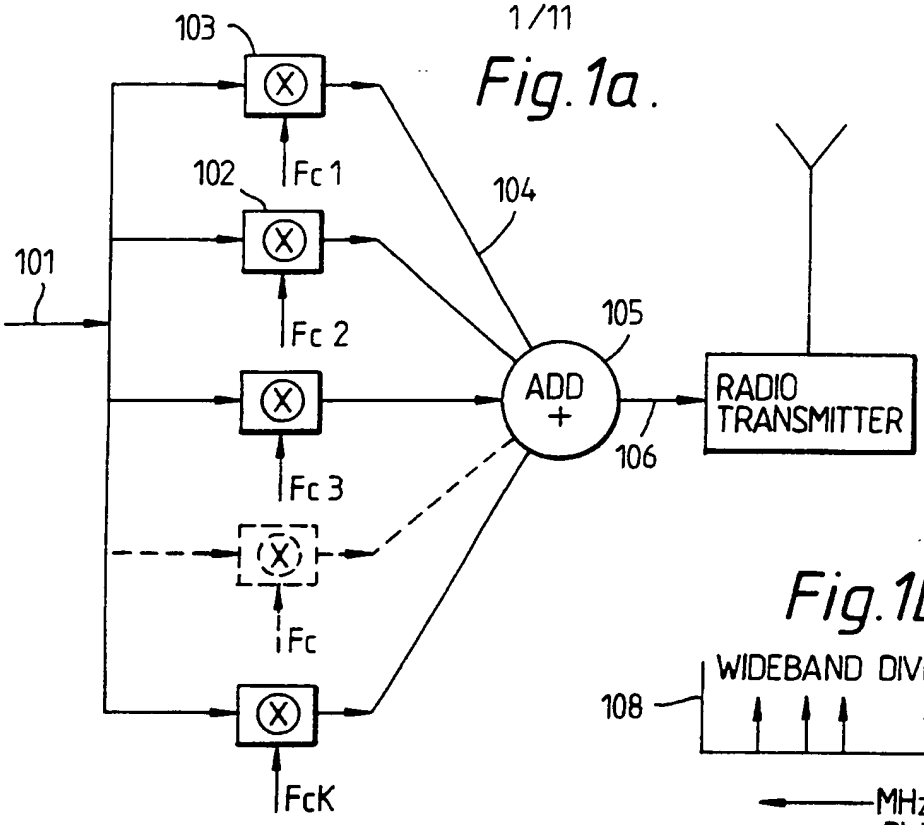


Fig.1b.

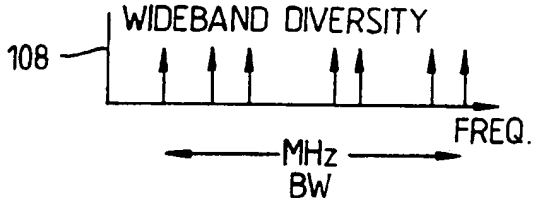


Fig.1d.

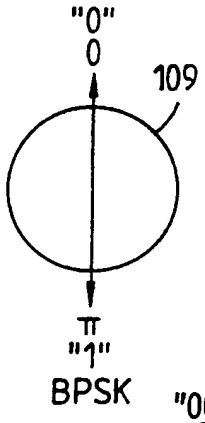


Fig.1c.

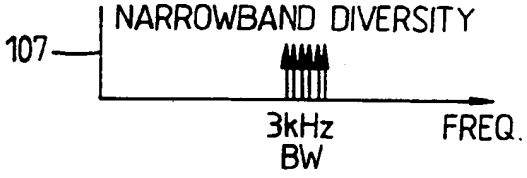


Fig.1e.

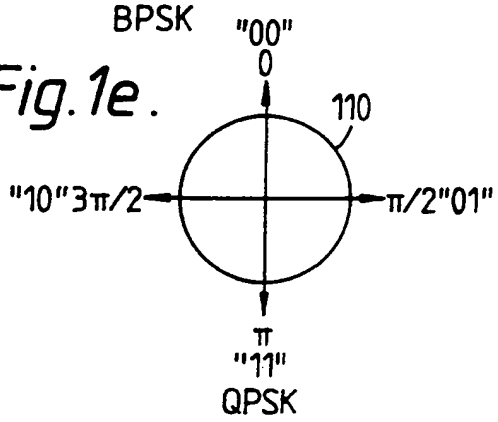


Fig.1f.

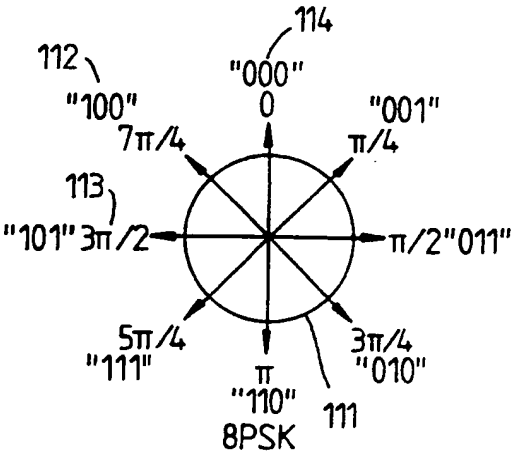


Fig.2.

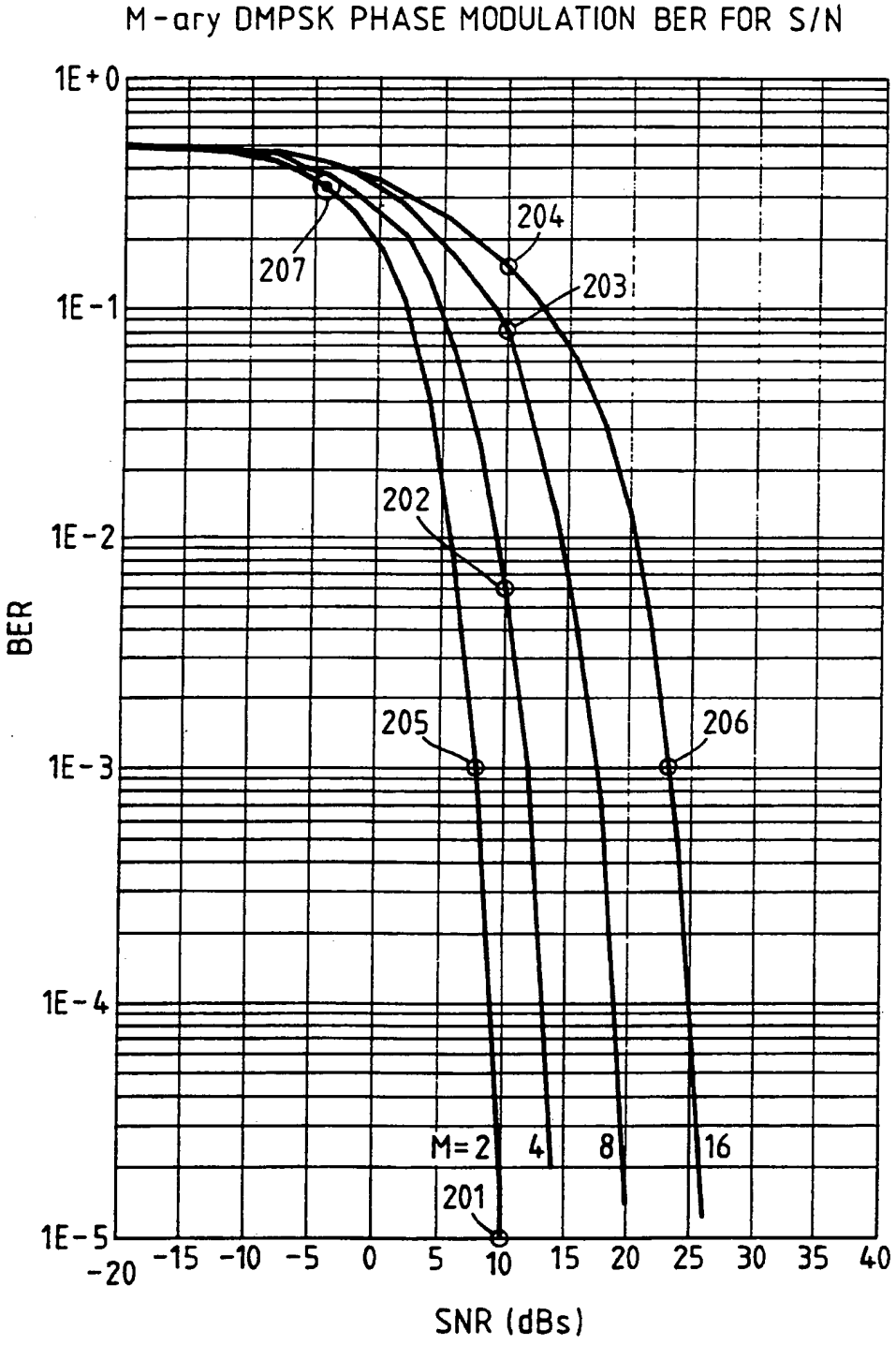

M-ary DMPSK PHASE MODULATION BER FOR S/N
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
BER
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
SNR (dBs)
207
204
203
202
205
206
M=2
4
8
16
201

Fig. 3.

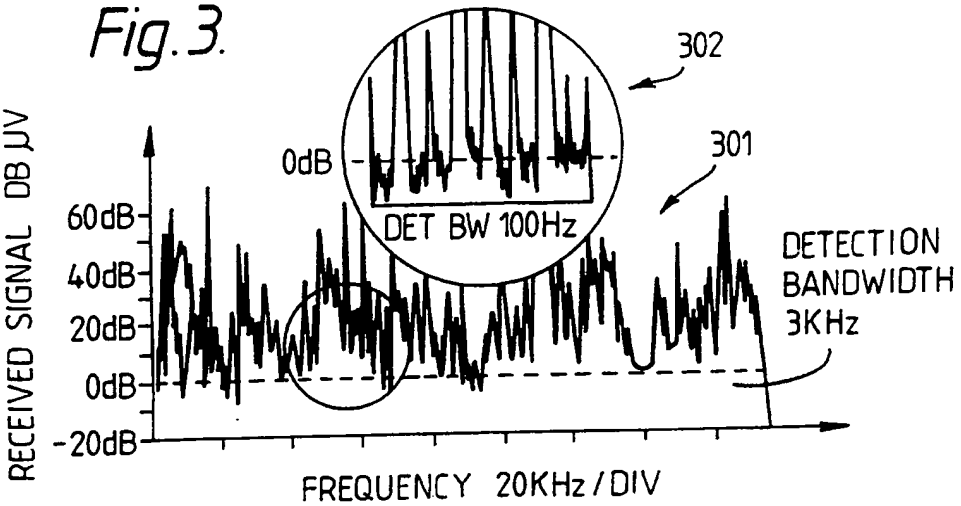

302
301
0dB
DET BW 100Hz
DETECTION
BANDWIDTH
3KHz
RECEIVED SIGNAL DB µV
60dB
40dB
20dB
0dB
-20dB
FREQUENCY 20KHz / DIV

Fig. 4.

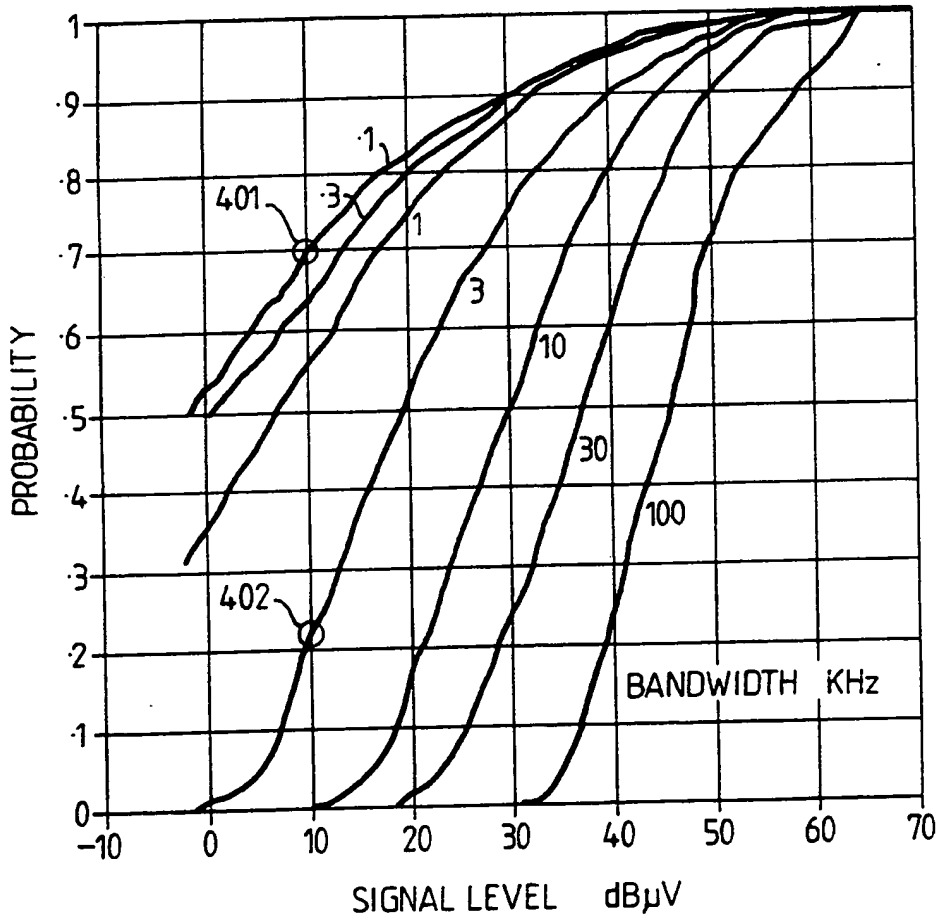
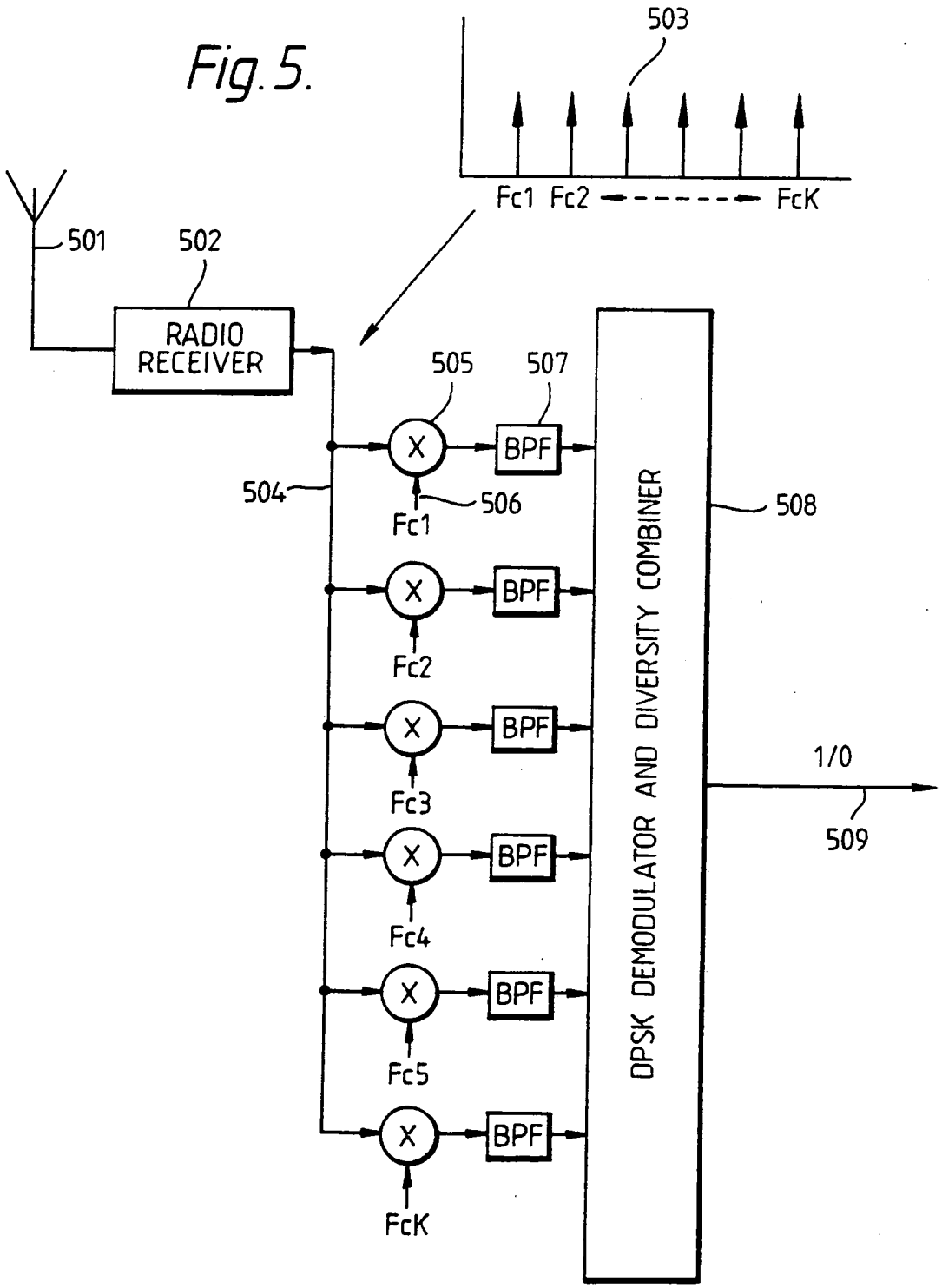

PROBABILITY
1
·9
·8
·7
·6
·5
·4
·3
·2
·1
0
401
402
·1
·3
1
3
10
30
100
BANDWIDTH KHz
−10
0
10
20
30
40
50
60
70
SIGNAL LEVEL dBµV

Fig. 5.


503
Fc1 Fc2 FcK
501
502
RADIO RECEIVER
505
507
X
BPF
504
506
Fc1
508
Fc2
Fc3
Fc4
Fc5
FcK
DPSK DEMODULATOR AND DIVERSITY COMBINER
1/0
509

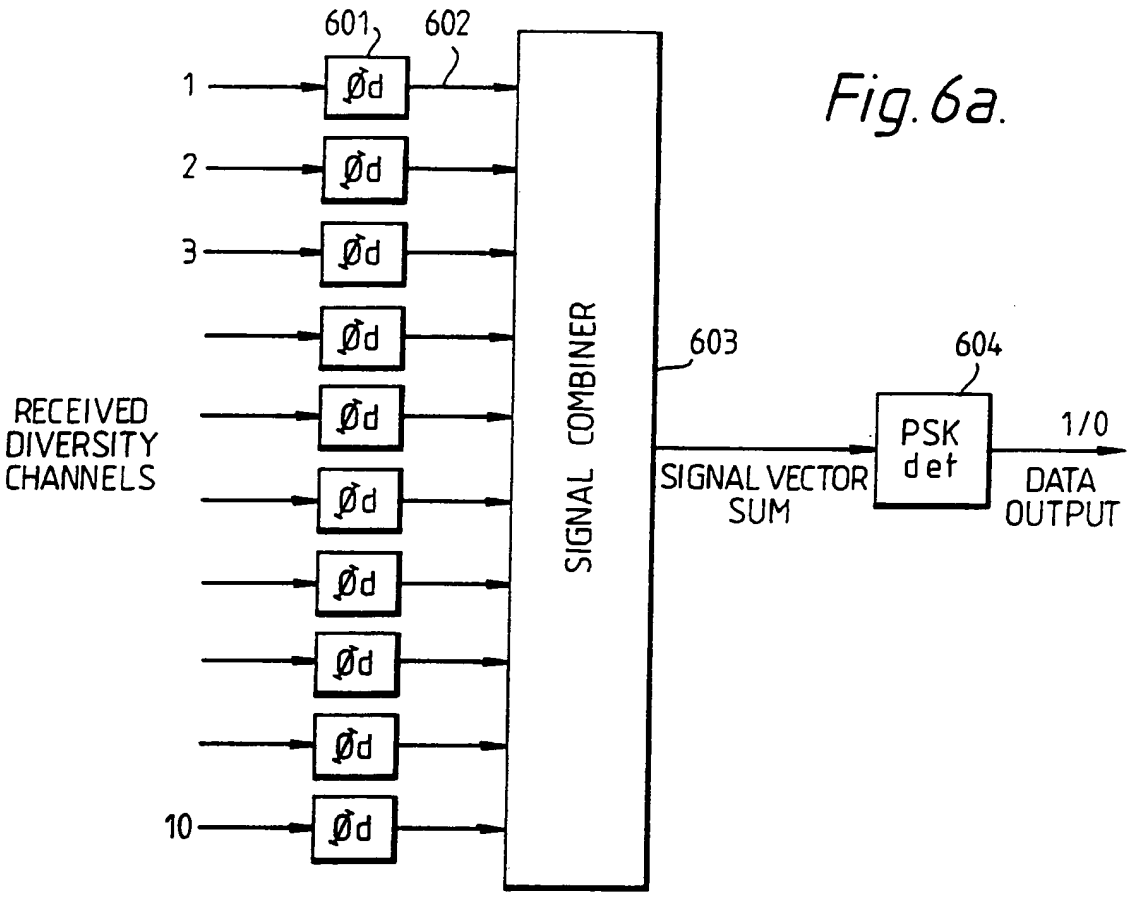


Fig. 6a.

Fig. 6b.

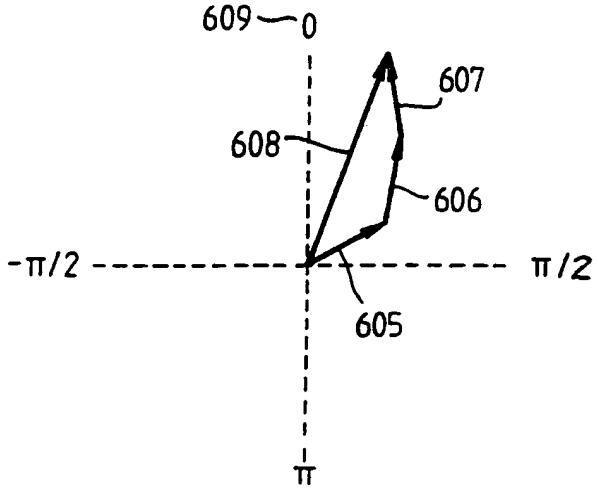


Fig. 6c.

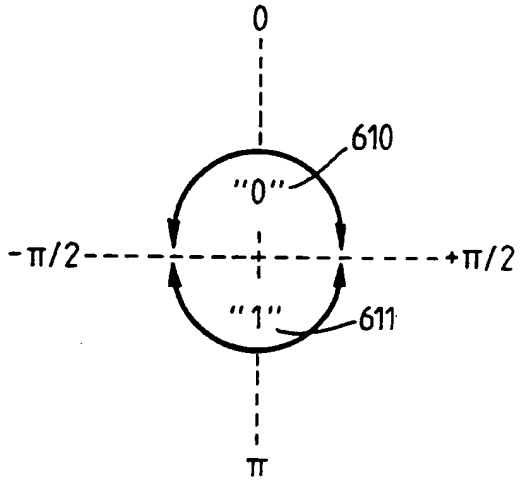


Fig.6d.

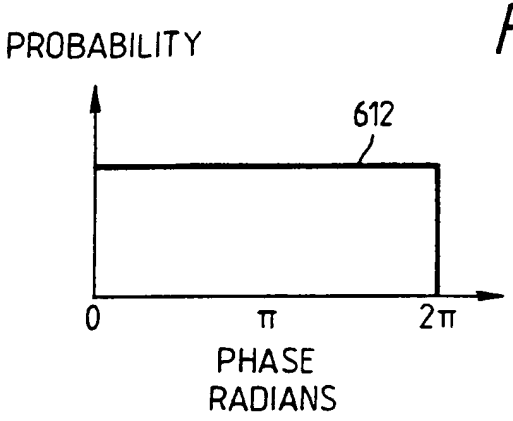


Fig.6e.

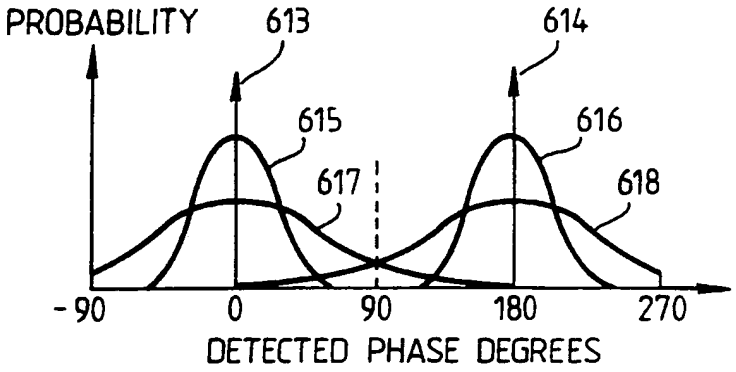


Fig.6f.

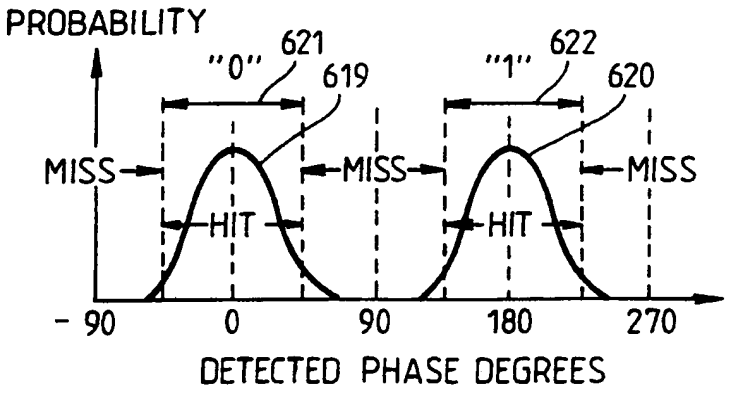


Fig. 6g.

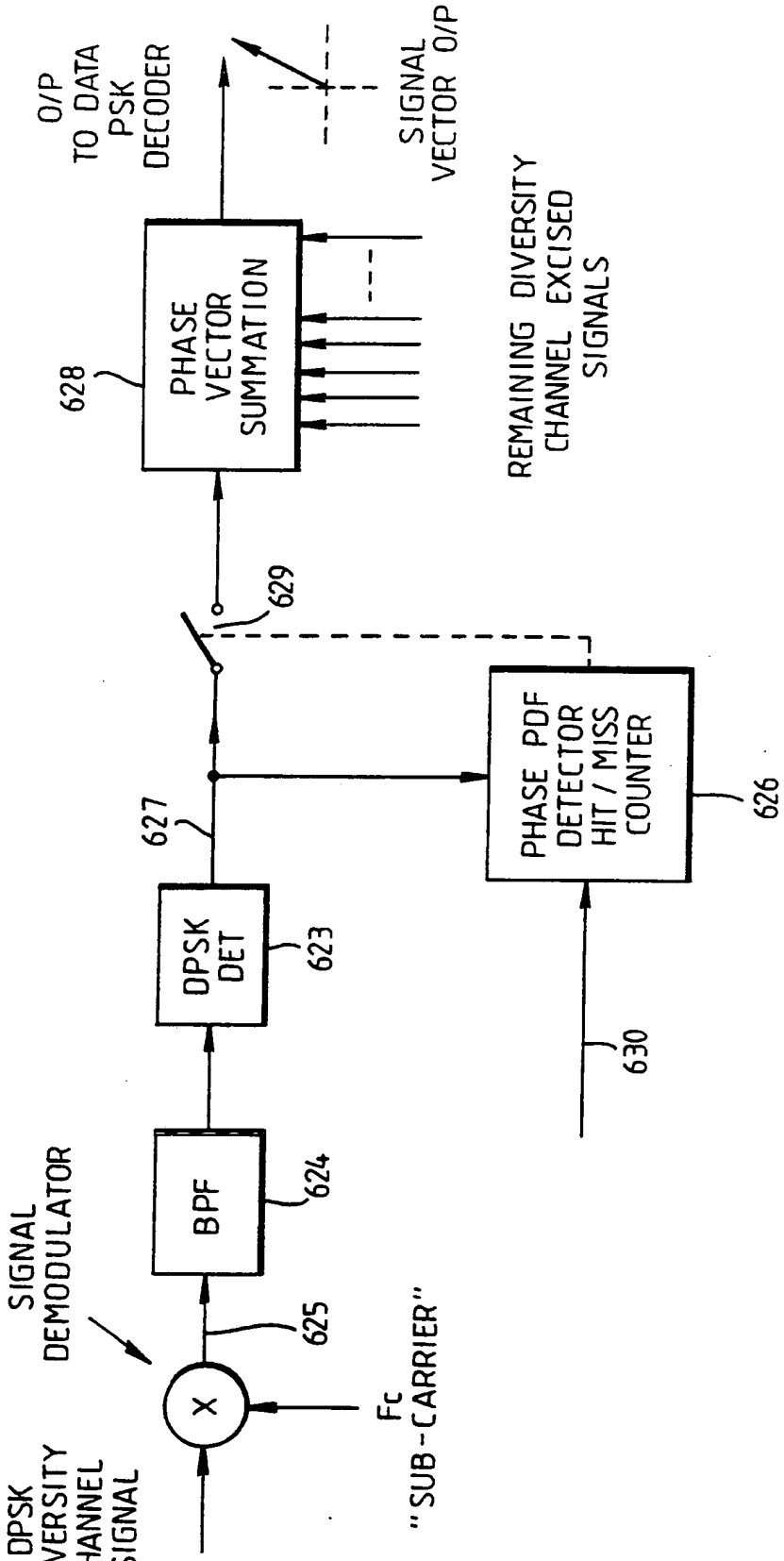

DPSK DIVERSITY CHANNEL SIGNAL
SIGNAL DEMODULATOR
X
Fc "SUB-CARRIER"
625
BPF
624
DPSK DET
623
627
629
628
PHASE VECTOR SUMMATION
O/P TO DATA PSK DECODER
SIGNAL VECTOR O/P
REMAINING DIVERSITY CHANNEL EXCISED SIGNALS
PHASE PDF DETECTOR HIT / MISS COUNTER
626
630

Fig. 7.

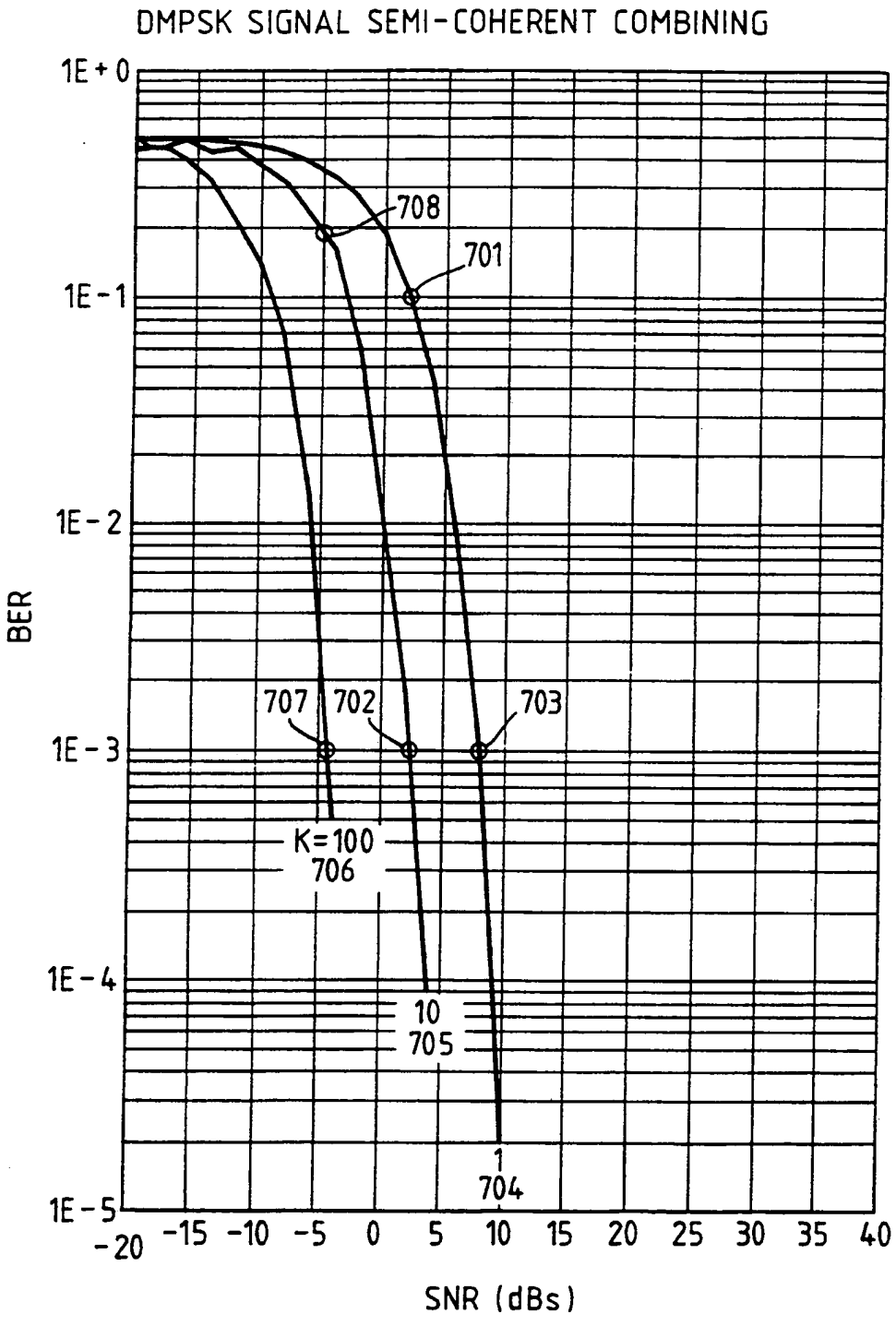

DMPSK SIGNAL SEMI-COHERENT COMBINING
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
BER
708
701
707
702
703
K=100
706
10
705
1
704
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
SNR (dBs)

Fig. 8.

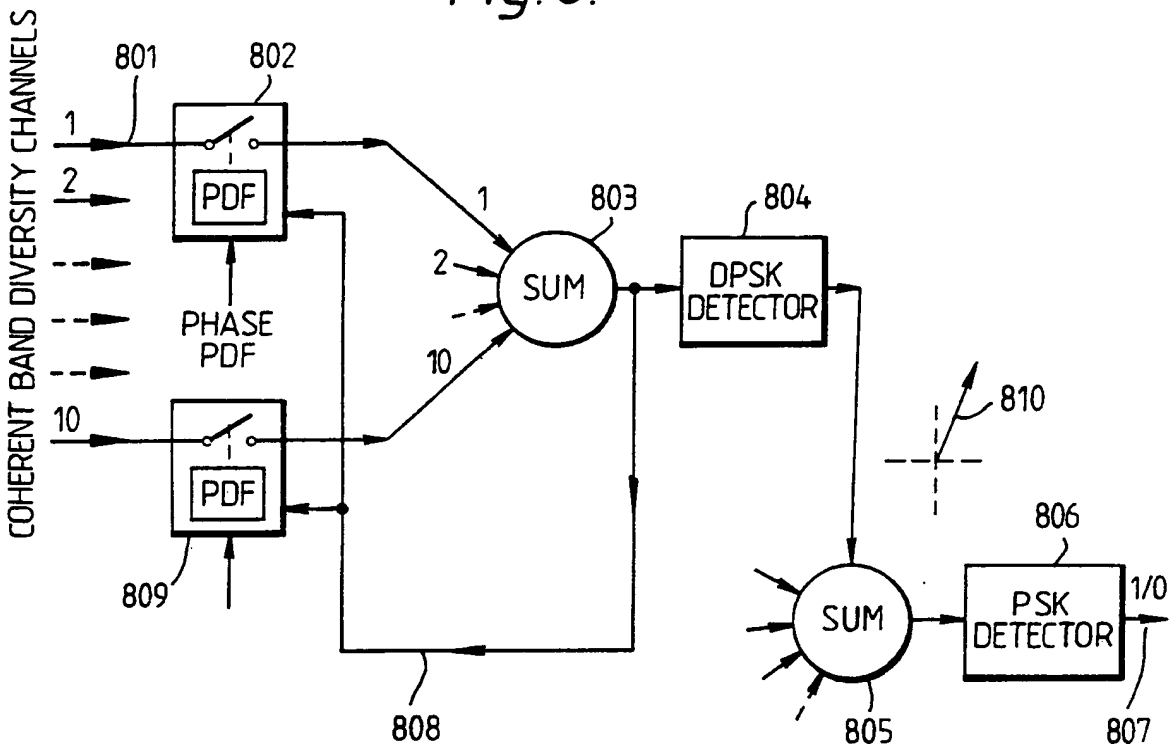

COHERENT BAND DIVERSITY CHANNELS
801
802
1
2
10
PDF
PHASE PDF
PDF
809
1
2
10
803
SUM
804
DPSK DETECTOR
810
806
SUM
PSK DETECTOR
1/0
805
807
808

Fig. 10.

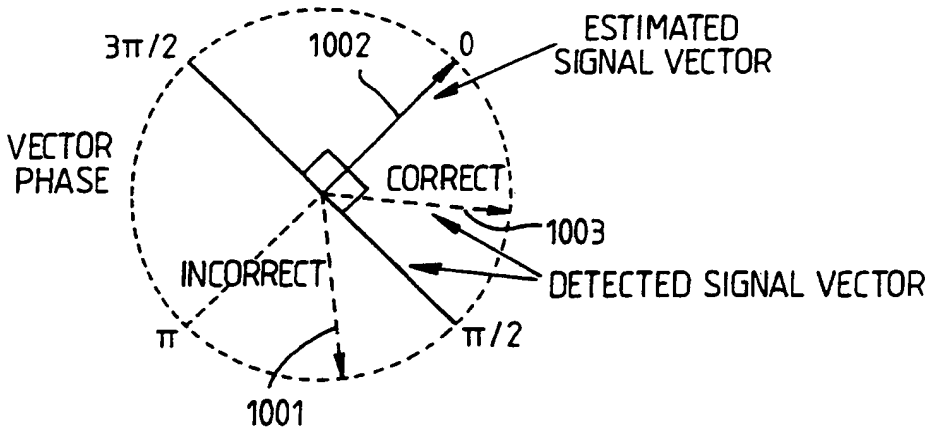

3π/2
1002
0
ESTIMATED SIGNAL VECTOR
VECTOR PHASE
CORRECT
1003
INCORRECT
DETECTED SIGNAL VECTOR
π
π/2
1001

Fig. 9.

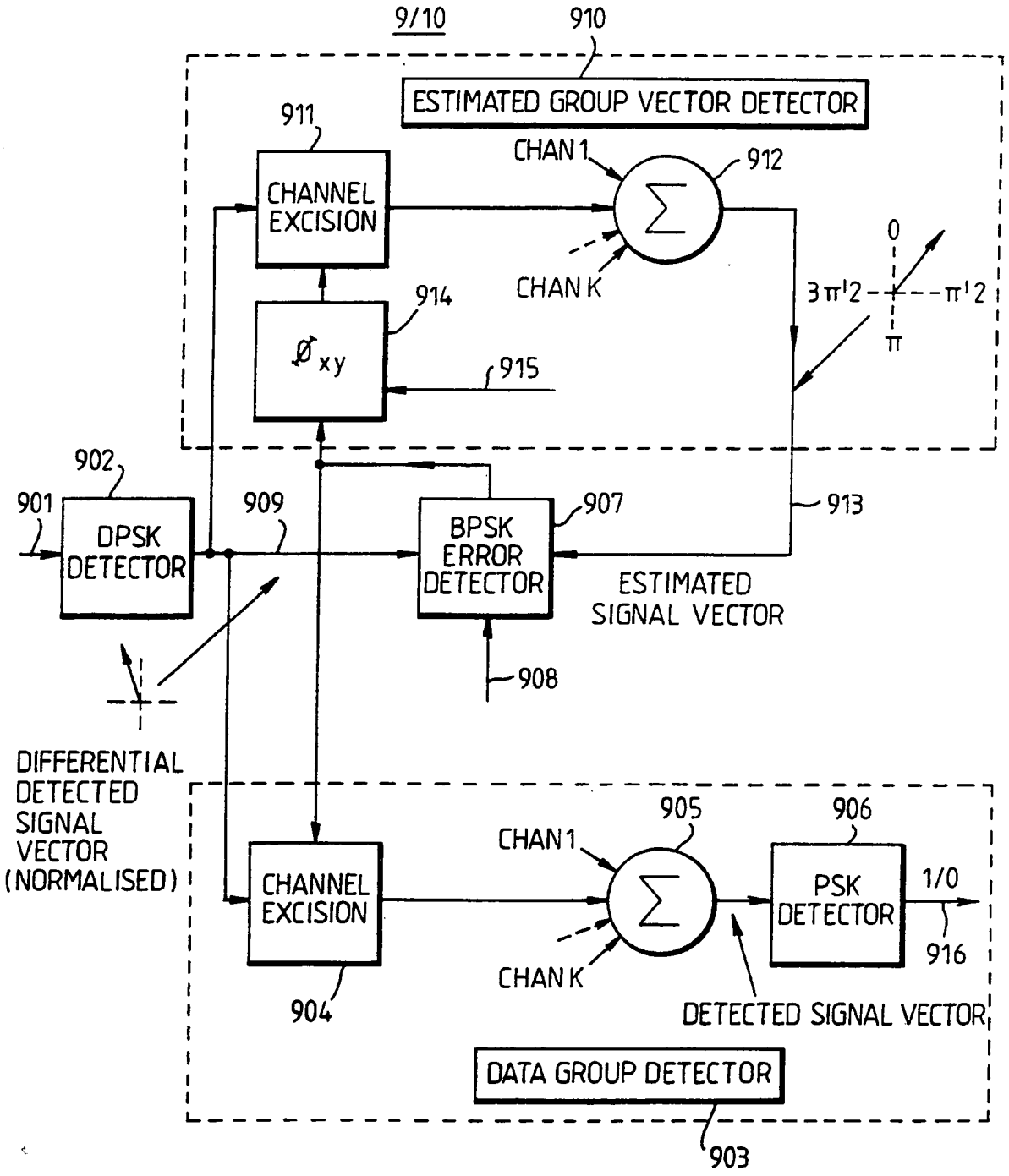

9/10
910
ESTIMATED GROUP VECTOR DETECTOR
911
CHANNEL EXCISION
CHAN 1
912
CHAN K
914
$\emptyset_{xy}$
915
0
3π/2
π/2
π
902
901
DPSK DETECTOR
909
BPSK ERROR DETECTOR
907
913
ESTIMATED SIGNAL VECTOR
908
DIFFERENTIAL DETECTED SIGNAL VECTOR (NORMALISED)
905
906
CHAN 1
CHANNEL EXCISION
PSK DETECTOR
1/0
916
CHAN K
904
DETECTED SIGNAL VECTOR
DATA GROUP DETECTOR
903

Fig. 11.

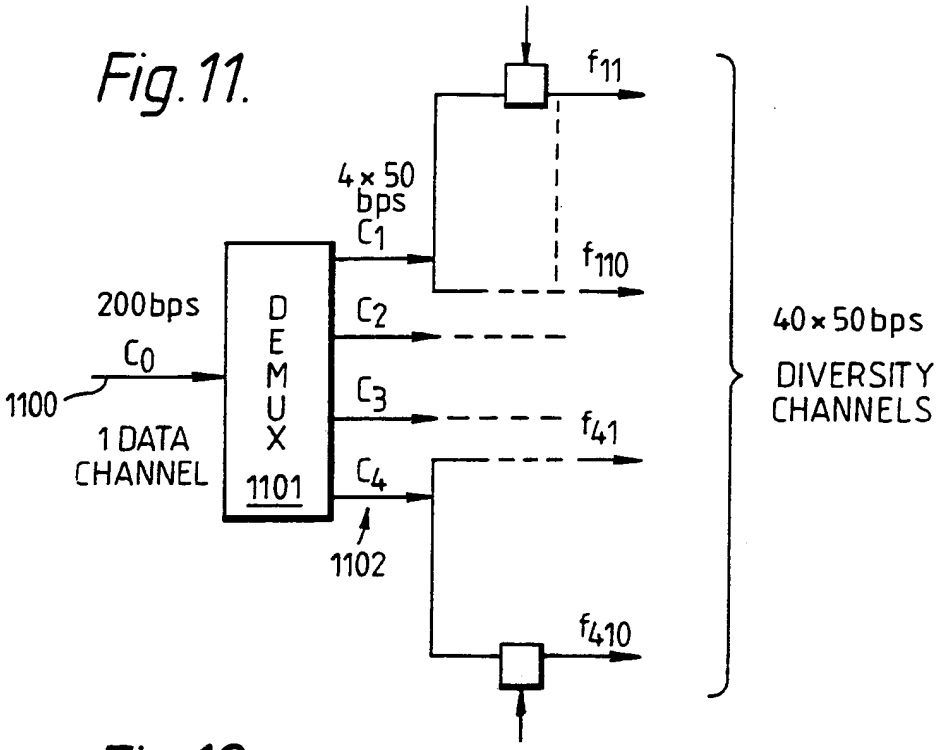
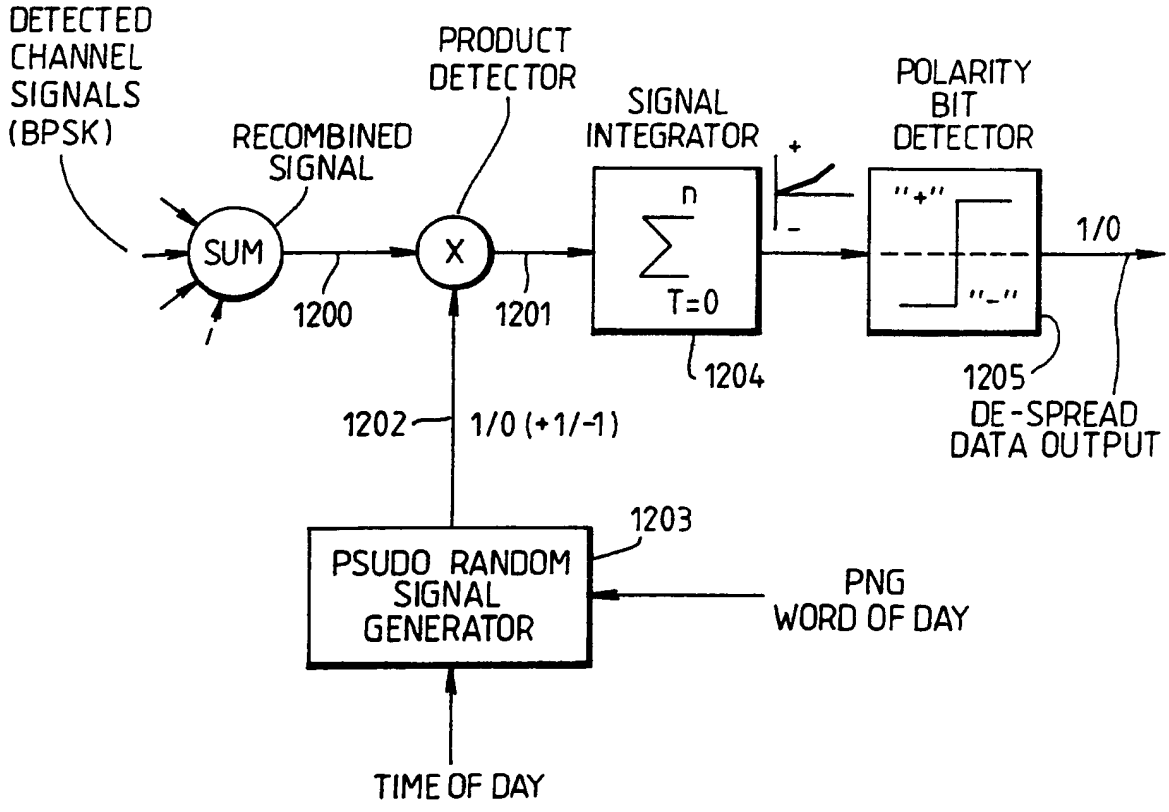

f11
4 x 50 bps
C1
f110
200bps
C0
C2
40 x 50bps
DIVERSITY CHANNELS
1100
1 DATA CHANNEL
DEMUX 1101
C3
f41
C4
1102
f410

Fig. 12.


DETECTED CHANNEL SIGNALS (BPSK)
RECOMBINED SIGNAL
PRODUCT DETECTOR
SIGNAL INTEGRATOR
POLARITY BIT DETECTOR
SUM
X
n
Σ
T=0
+
-
"+"
"-"
1/0
1200
1201
1204
1205
DE-SPREAD DATA OUTPUT
1202
1/0 (+1/-1)
1203
PSUDO RANDOM SIGNAL GENERATOR
PNG WORD OF DAY
TIME OF DAY

INTERNATIONAL SEARCH REPORT

International Application No PCT/GB 9100682

I. CLASSIFICATION OF SUBJECT MATTER (if several classification symbols apply, indicate all)[6]

According to International Patent Classification (IPC) or to both National Classification and IPC

H 04 L 1/04 H 04 B 7/12

II. FIELDS SEARCHED

Minimum Documentation Searched[7]

Classification System	Classification Symbols
Int.Cl.5	H 04 L H 04 B

Documentation Searched other than Minimum Documentation to the Extent that such Documents are Included in the Fields Searched[8]

III. DOCUMENTS CONSIDERED TO BE RELEVANT[9]

Category °	Citation of Document, [11] with indication, where appropriate, of the relevant passages [12]	Relevant to Claim No.[13]
X	GB-A-2 161 344 (PHILIPS) 8 January 1986, see column 1, line 30 - column 1, line 45; figures 2,3	1-6
A	US-A-4 419 766 (GOEKEN et al.) 6 December 1983, see column 6, line 8 - column 6, line 57; figure 2	1,7-10
A	EP-A-0 065 764 (SIEMENS) 1 December 1982, see abstract; figure 1	1,11-14
A	EP-A-0 309 855 (ZELLWEGER) 5 April 1989, see column 3, line 2 - column 3, line 5	1,21
A	DE-A-3 338 510 (ANT) 2 May 1985, see abstract; figure 1	1,7-10

° Special categories of cited documents : [10]

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

IV. CERTIFICATION

Date of the Actual Completion of the International Search	Date of Mailing of this International Search Report
31-07-1991	17.09.91
International Searching Authority	**Signature of Authorized Officer**
EUROPEAN PATENT OFFICE	miss T MORTENSEN

Form PCT/ISA/210 (second sheet) (January 1985)

ANNEX TO THE INTERNATIONAL SEARCH REPORT ON INTERNATIONAL PATENT APPLICATION NO. GB 9100682

SA 47128

This annex lists the patent family members relating to the patent documents cited in the above-mentioned international search report. The members are as contained in the European Patent Office EDP file on 06/09/91
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent document cited in search report	Publication date	Patent family member(s)		Publication date
GB-A- 2161344	08-01-86	None		
US-A- 4419766	06-12-83	CA-A-	1183219	26-02-85
EP-A- 0065764	01-12-82	DE-A-	3121146	05-01-83
		AU-B-	530445	14-07-83
		AU-A-	8419582	02-12-82
		CA-A-	1198169	17-12-85
		JP-A-	57199356	07-12-82
		US-A-	4628517	09-12-86
EP-A- 0309855	05-04-89	CH-A-	673550	15-03-90
		US-A-	5005209	02-04-91
DE-A- 3338510	02-05-85	None		